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THERMAL ENERGY MEASUREMENT WITH TANGENTIAL PADDLEWHEEL FLOW METERS: SUMMARY OF EXPERIMENTAL RESULTS AND IN-SITU DIAGNOSTICS

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ABSTRACT

Recently third-party financing has become a popular mechanism for funding energy conservation retrofits in commercial/institutional buildings. Although many successful projects have been heralded by the press quite a few projects have either ended in litigation or have required arbitration when the actual utility bill savings did not match the negotiated savings (Haberl 1992). This has prompted state and federal officials to develop consensus standards¹ that could be used to obtain some sort of accurate measurement across different projects.

Unfortunately, the need for accurate measurement is often stifled in such projects due to tight budget constraints where the building owner may not be willing to pay the additional 5 to 10% cost to pay for the detailed measurement of the savings. However, since these projects often involve the transfer of large amounts of money to repay the third-party that finances the retrofit any measurement that is taken should be considered a revenue transfer measurement². In energy conservation retrofits flow measurements are typically required for the analysis of thermal energy use such as chilled water, hot water and steam condensate use. In applications where the accumulated or totalized energy use is needed microprocessor-based thermal energy meters, or "Btu meters" are often used to integrate and display flow and energy data or generate a totalized signal for input into a data acquisition system.

In this paper a summary of experimental results from calibration efforts in the Texas LoanSTAR program are presented, including the premature drop-out of magnetic-type tangential paddlewheel flow meters, and several new methods for in-situ diagnostic measures for ascertaining whether or not a

flow meter is experiencing fluctuating flow conditions or if a flow meter is suffering a degraded signal due to shaft wear.

INTRODUCTION

Flow measurement is an important part of the analysis of building energy use whenever thermal energy use is being investigated. In a building accurate, yet affordable liquid flow measurements are required for the analysis of chilled water, hot water and steam condensate use. Currently, in applications where the accumulated or totalized energy use is needed microprocessor-based thermal energy meters, or Btu meters are often used to integrate and display flow and energy data or generate a totalized signal that can be recorded by data acquisition system. The accuracy of totalized flow and thermal energy measurements is directly effected by the quality of temperature and flow measurement sensors.

In a closed-loop system a thermal energy meter requires at least three input signals: a signal that is proportional to the liquid flow rate, and signals for the temperatures in both the supply and return lines as shown in Figure 1 (Watt and Haberl 1994). In most thermal meters that are commercially available three quantities are being measured, the supply and return temperatures and the fluid flow rate; and two quantities are being totalized and displayed (or output), the fluid flow, and the thermal energy use. The totalized thermal energy use represents the continuous multiplication of the difference between the supply and return temperatures times the mass flow rate specific heat product.

¹ One of the important consensus methods is ASHRAE's GPC 14P which was recently formed to develop guidelines for measuring energy conservation retrofits for Demand Side Management programs.

² This term is also referred to as a "custody transfer measurement" (Miller 1989, p. 14.2).

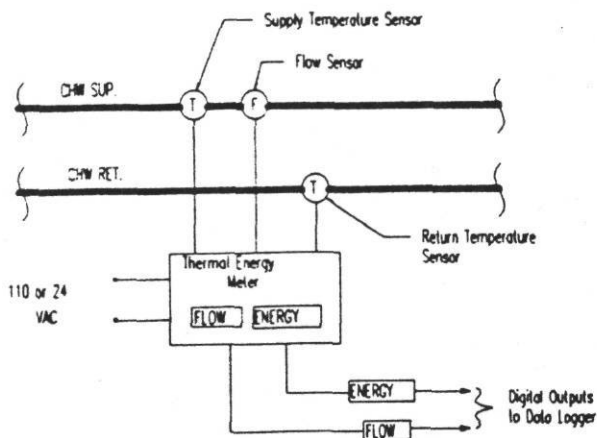


FIGURE 1: TYPICAL THERMAL ENERGY METER SET-UP. THIS FIGURE SHOWS A TYPICAL THERMAL ENERGY METER (BTU METER) SET-UP THAT IS USED TO MEASURE ENERGY USE IN CHILLED WATER AND HOT WATER SYSTEMS (BOECKER ET AL. 1992).

The flow measurement signal is usually transmitted to the thermal energy meter as a digital pulse signal or varying analog voltage signal from the tangential paddlewheel flow sensor which is inserted into the fluid-carrying pipe.

In the previous study a survey was performed³ that show that the installed cost of a thermal energy meter can vary significantly depending on the flow meter specified (Haberl et al. 1992b). In this survey it was found that purchase costs for different flow meters varies from \$500 to \$3,500, installation costs varied from \$500 for a two-inch (5.1 cm) wet tap to \$1500-\$2000 for installation where the pipe must be drained, cut and welded. In most cases there is an economic incentive to use a less expensive flow meter in those installations where the fluid velocity is above the drop-out threshold. The least expensive meters can cost as little as \$800 (installed), whereas, the most expensive meters can run \$20,000 and more for installations where large piping is encountered.

For those meters where a rotating wheel is inserted into the flow stream volumetric flow meters are usually specified through the use of a published "K-factor" or pulse-per-gallon (PPG) factor that converts the electronic pulse coming from the flow sensor into volumetric measurements per unit time as required by the thermal energy meter.

In the previous works (Turner et al. 1992; Haberl et al. 1992a; Robinson 1992, O'Neal et al. 1990, Watt and Haberl 1994) it was shown that the accuracy of thermal energy measurements in buildings can be compromised by inaccuracies in the flow measurements, including: errors in the manufacturer's pulse-per-gallon constants, errors due to improper insertion depth, and errors due to a drop-out in the meter signal at low-velocity fluid flows. In the previous studies

³ This survey was performed in 1992 as part of the Texas LoanSTAR program.

significant effort was devoted to measuring the accuracy of several different types of meters at varying fluid velocities, pipe diameters, and distance/orientation from nearby elbows (Parker and O'Neal 1995) using a dynamic weigh facility specially contracted for this purpose⁴.

K-factors, or meter-factor signature curves are sometimes available from manufacturers, or in metering text books (Miller 1989). The signal drop-out problem for magnetic-type flow meters is not a new problem and has been reported in numerous journals dating as far back as 36 years ago⁵ (Hochreiter 1958). However, there seems to be an unwillingness among some manufacturers to make it very clear to installers that different types of flow meters have different lower velocity thresholds below which data are virtually meaningless. Often times when a flow meter

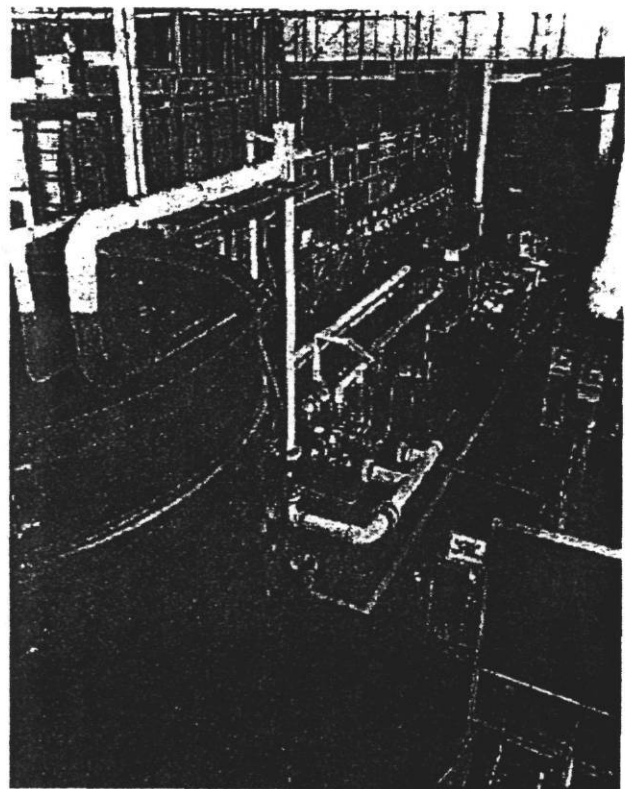


FIGURE 2: PHOTOGRAPH OF THE LIQUID FLOW LOOP CALIBRATION FACILITY.

⁴ Parker and O'Neal have also calculated the experimental error for the dynamic weigh test facility.

⁵ Hochreiter's work was reported for turbine meters carrying different types of hydrocarbons. However, the non-dimensional meter coefficient imply similar meter drop-out in measurements involving water. On page 1365 Hochreiter referred to the fact that "At low speeds deviations occur because bearing friction, enhanced by the radial loading of the magnetic pickup is no longer negligible compared to the fluid forces". In other words, the published linear relationship no longer applies below a certain point.

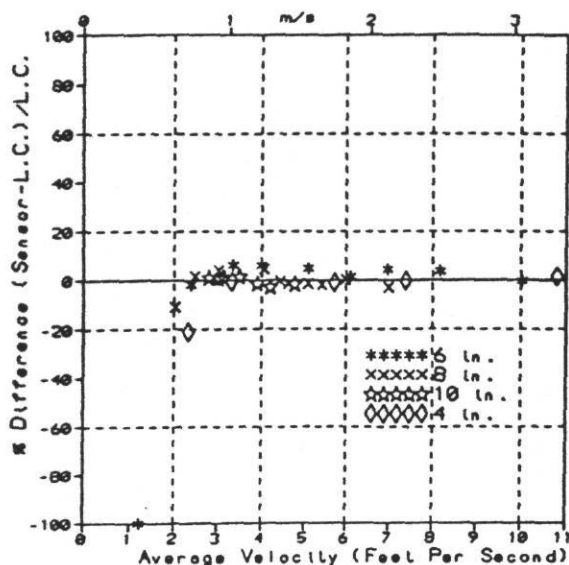


FIGURE 3A: RESULTS OF TESTS OF TANGENTIAL PADDLEWHEEL FLOW METERS. THIS FIGURE SHOWS THE RESULTS OF TESTS THAT WERE PERFORMED ON MAGNETIC-TYPE TANGENTIAL PADDLEWHEEL FLOW METERS USING A DYNAMIC WEIGH FLOW LOOP (ROBINSON ET AL. 1992)

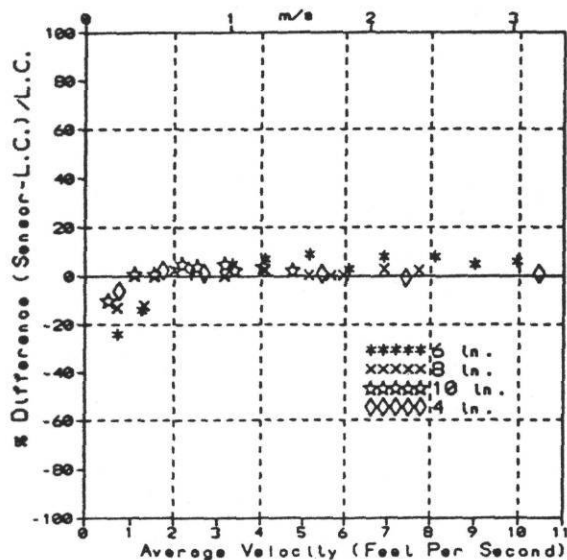


FIGURE 3B: RESULTS OF TESTS OF TANGENTIAL PADDLEWHEEL FLOW METERS. THIS FIGURE SHOWS THE RESULTS OF TESTS THAT WERE PERFORMED ON NON-MAGNETIC-TYPE TANGENTIAL PADDLEWHEEL FLOW METERS USING A DYNAMIC WEIGH FLOW LOOP (ROBINSON ET AL. 1992)

water is drawn out of the supply tank at varying flow rates and pumped through the test section where it passes across the

candidate sensor that is placed in the inter-changeable test section, through the orifice plate and finally into the is combined with Btu meter the threshold can be much higher than the published threshold of the flow meter by itself. This paper will present results from experiments performed on a dynamic-weigh flow test facility that show that certain combinations of magnetic flow meters and thermal energy meters (i.e., Btu meters) can raise the drop-out threshold from 1 ft/sec (0.31 m/s) to as high as 3 ft/s (0.91 m/s).

In the LoanSTAR program a dynamic weight liquid flow loop is used to calibrate meters. In the flow loop water is drawn out of the supply tank at varying flow rates and pumped through the test section where it passes across the candidate sensor that is placed in the inter-changeable test section, through the orifice plate and finally into the receiving tank where it is continuously weighed as shown in Figure 2.

A data acquisition system is used to sample the signal from the load cells that measure the changing weight of the water as a primary standard to the volumetric liquid flow rate (Turner et al. 1992). The orifice plate is used as a secondary standard. Figures 3a,b give a summary of the results of calibrations in pipes varying in size from 4 to 10 inches (10.2 to 25.4 cm) for magnetic (Figure 3a) and non-magnetic (Figure 3b) flow meters.

Results from the previous tests of tangential paddlewheel flow meters indicated that flow measurements below fluid velocities of 3 ft/s (0.914 m/s) for magnetic-type, and 1 to 2 ft/s (0.305 to 0.610 m/s) for non-magnetic-type flow sensors deviated from the actual flow by 10% or more which makes the measurement of flow and thermal energy use in this regime unreliable.

With the exception of the tests from the 6 inch pipe⁶ (15.2 cm) the magnetic and non-magnetic meters performed well within the manufacturer's specifications (Table 1).

The coefficient of variation of the root mean squared error CV(RMSE)⁷ for the magnetic meters tested in 4, 8 and 10 inch pipes (10.1, 20.3, 24.5 cm) was 1.99%. The mean bias error was -0.11%. CV(RMSE) of the non-magnetic meters was 2.31%, MBE was +1.8%. Overall results of both meters combined showed a CV(RMSE) of 2.13% and MBE of +0.81%.

Unfortunately, during the initial stages of the LoanSTAR program it was discovered that several of the sites that had flow below 2 ft/s (0.610 m/s) had magnetic-type meters that were not operating properly. This required the replacement of the offending meters with non-magnetic-type meters in order to

⁶ Tests performed on the 6 inch pipe were performed prior to the installation of a flow straightener 20+ diameters upstream of the flow meter. These tests show a CV(RMSE) of 5.67% and a MBE of +7.74% which indicated that the flow meters were very sensitive to flow fluctuations in the pipe. The +7.74% MBE was believed to be caused by a piping arrangement that is common in field conditions where flow from a smaller pipe is injected into a larger, fluid carrying pipe.

⁷ Equations for the CV(RMSE) and MBE are included in the appendix.

obtain more reliable measurements in the low flow installations. A significant amount of the valuable pre-retrofit data from these sites was not recoverable.

From Figure 4 it can be clearly seen that low-velocity flow conditions represents a significant portion of the buildings being monitored⁸. Similar conditions are expected in buildings in other locations as well. This can present a dilemma for large-scale monitoring program administrators because the cost of an installed meter can increase significantly whenever a more expensive flow sensor must be specified or when a special metering leg⁹ must be inserted to divert the flow through a smaller diameter pipe.

In this paper two additional aspects have been investigated that supplement the previous work. First, when one compares Figure 3a to 3b it is evident that the paddlewheels which use a magnetic-type pickups experience an earlier drop-out in the signal than paddlewheels that utilize a non-magnetic pickup. This is due to the different technologies that are used to sense the rotating wheel. In the magnetic flow meter magnets are used in the rotor blades to generate a sinusoidal mV signal

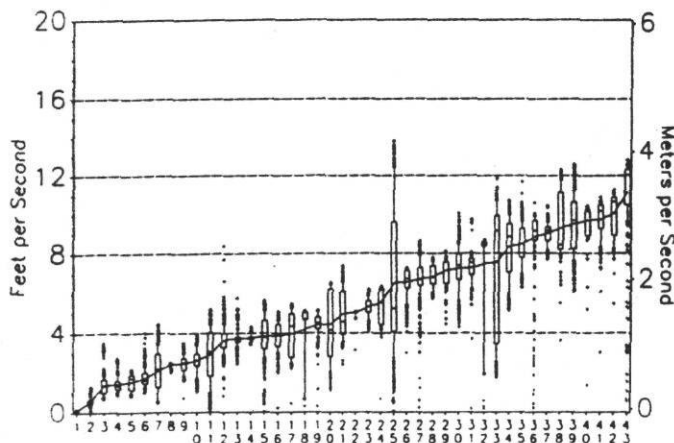


FIGURE 4: MEASURED FLOW VELOCITIES IN HVAC THERMAL PIPING SYSTEMS. THIS FIGURE SHOWS TYPICAL MEASURED FLOW VELOCITIES IN SELECTED AGENCIES PARTICIPATING IN THE LOANSTAR PROGRAM. THE VELOCITIES MEASUREMENTS SHOWN REPRESENT ONE MONTH IN AUGUST 1994.

that varies in period and amplitude as the water velocity increases. The non-magnetic flow meters utilized an RF transmitter/receiver that generates a carrier frequency that is

⁸ The data in Figure 4 are for the following sites beginning with site #1 = ZEChw, ZEChw, SPH, GEA, EDB, UTC, GAR, MLB, BSB, #10 = BUR, UTHcwe, SHBhw, JHR, CSB, NUR, UTHcwe, SFA, VHSw2, TAG, #20 = UTP, PCL, JHW, JSN, WBT, UNV, MDAcw, SHBcwah, JSS, TDH, #30 = MSB, MDAcw2, VHSw1, FNA, WAG, WELcw10, MDAcw1, BUS, SHBcwau, WELcw4, #40 = LBJ, MDAcw3, SHBcwot, MDAcw4.

⁹ These metering legs can be very costly, ranging from \$1,000 to \$10,000 in very large pipes.

broken with the passing of the rotor blades between the transmitter and receiver which generates an inverted pulse of constant amplitude.

The premature¹⁰, low-flow drop-out of the magnetic meter will be shown to be caused by a mismatch between the lack of strength of the mV output signal from the flow sensor and the threshold sensitivity of the input signal to the thermal energy meter. Second, several in-situ field diagnostics are presented for ascertaining whether or not a flow meter is experiencing turbulent conditions and whether or not a flow sensor's output signal is suffering a degraded signal due to shaft wear¹¹. These diagnostics were developed to reduce recalibration costs in the field maintenance program for the Texas LoanSTAR program¹².

CURRENT WORK

Several new experiments were investigated in the current work to determine why the low flow problems were occurring in magnetic and non-magnetic tangential paddlewheel flow meters¹³. In order to investigate the wave form output of a rotating flow meter, an experimental test bench was constructed as shown in Figure 5. A variable auto transformer was used to control the blower which forced air through a clear Plexiglas test section and across the paddlewheel. This procedure allowed the rotational speed of the paddlewheel to be quickly varied to any desired frequency as measured by an oscilloscope. In addition, a strobe light was used to directly measure the rotational speed of the paddlewheel and served as a secondary measure of the paddlewheel frequency. A ten-diameter entry length followed a screen mesh and tube bank flow straightener set-up to insure fully developed turbulent flow (Baker and Hurley 1984). Velocity profiles, obtained by traversing the test section with a 1/16" (1.6 mm) diameter pitot tube, are shown in Figure 6. A controllable range of 0 - 57 Hz for the non-magnetic-type tangential paddlewheel flow meter and 0 - 25 Hz for the magnetic-type flow meter was attainable using this set-up. The wave form generated by the meters was

¹⁰ We use the word "premature" here is to indicate that the manufacturer of these meters states that the meters are valid from 1 to 30 ft/s. However, when combined with a Btu meter these meters consistently fail to record flow below 3 ft/s.

¹¹ An early version of these diagnostics appeared in the paper by Watt and Haberl (1994).

¹² The Texas LoanSTAR program was designed to be an eight year, \$98.6 million revolving loan program for energy conservation retrofits in Texas state, local government and school buildings funded by oil overcharge dollars. As of 1994, the program was monitoring 3,000+ channels of hourly data from over 200 buildings, and seventy-five weather stations, using public domain polling procedures that collect information from microcomputer-based field data recorders supplied by several manufacturers. Additional information concerning the program can be found in Claridge et al. (1991; 1994).

¹³ These are the predominate type of flow meters used in the LoanSTAR program, other meters tested include: target-type meters, insertion-type axial turbine meters, and insertion-type shedding vortex meters.

monitored and electronically recorded with a digital storage oscilloscope¹⁴.

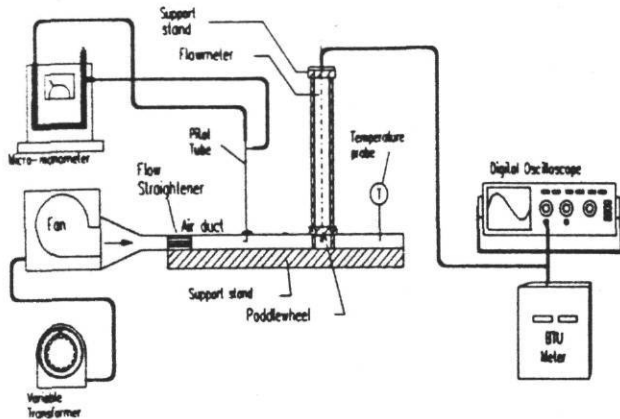


FIGURE 5: TEST SET-UP FOR THE CURRENT WORK. THIS IS THE TEST SET-UP FOR THE CURRENT WORK WHICH IS INTENDED TO INVESTIGATE THE CHARACTERISTICS OF THE OUTPUT SIGNAL FROM TANGENTIAL PADDLEWHEEL FLOW METERS.

To begin the testing, a quiescent state noise record was obtained for each type of flow meter by measuring the electronic noise on the leads to the flow meter when the meter was not rotating. The results are shown in Figure 7a (magnetic-type meter), and in Figure 7b (non-magnetic-type meter). It is clear when one compares Figures 7a and 7b that there is significantly more quiescent state noise with the magnetic-type flow meter than with the non-magnetic-type flow meter. It is felt that this is the major contributing factor to the signal drop-out in the magnetic-type flow meters below 3 ft/s (0.914 m/s).

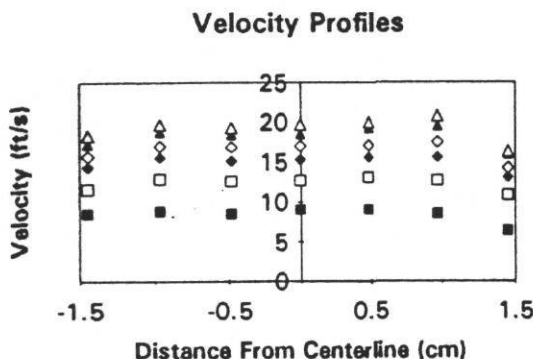


FIGURE 6: VELOCITY PROFILES FROM THE CURRENT TEST BENCH OBTAINED BY USING A 1/16" PITOT TUBE TRAVERSE.

One of the reasons for the increased noise is that the operating voltage of the magnetic-type flow meter is much less than that of the non-magnetic-type flow meter. The magnetic-type flow meter produces a sinusoid signal with peak amplitudes of 10 to 50 mV depending on the speed of rotation. Whereas, the non-magnetic type flow meter utilizes a DC input of apx. 8 volts to generate an inverted pulse of constant amplitude and width. To give an example of how this noise appears, Figure 8a and 8b have been provided. In these figures the signals from the respective flow meters are shown for velocities above 3 ft/s (0.914 m/s). Clearly, the non-magnetic-type flow meter is practically noise free.

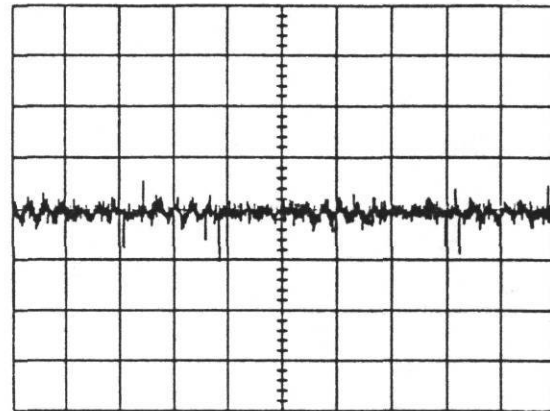


FIGURE 7A: (10 MV/DIV, 20 MSEC/DIV) NOISE ON QUIESCENT MAGNETIC-TYPE FLOW METER IN THE LABORATORY.

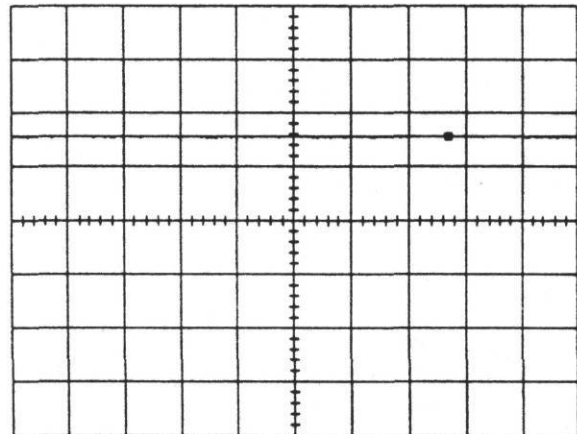


FIGURE 7B: (5 VOLTS/DIV, 10 MSEC/DIV) NOISE ON A QUIESCENT NON-MAGNETIC TYPE FLOW METER.

¹⁴ An equipment list for the experimental set up shown in Figure 5 was previously published in Watt and Haberl (1994).

Besides the noise problem, the magnetic-type meter experiences another problem at low flow rates in that a signal threshold exists below which certain thermal energy meters can no longer electronically pick up a signal even though the paddlewheel is still spinning and a weak signal is being generated. This problem depends on how noisy the mechanical room is where the sensor is located, how good the sensor and leads are shielded, and which brand of Btu meter has been specified. Based on these factors alone, the threshold can vary from 10 to 30 mV (Robinson 1992).

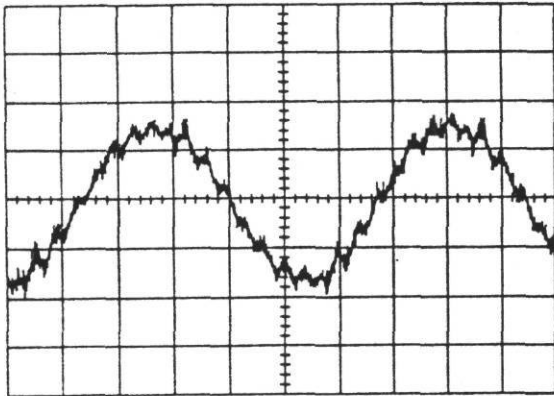


FIGURE 8A: (5 MV/DIV, 5 MSEC/DIV) TYPICAL SIGNAL GENERATED BY A MAGNETIC-TYPE FLOW METER WITH 60 HZ NOISE SUPERIMPOSED.

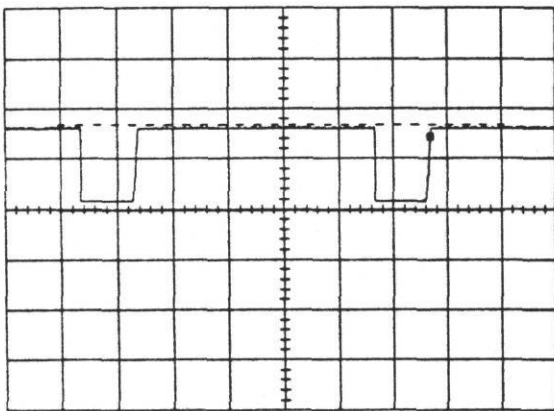


FIGURE 8B: (5 VOLTS/DIV, 5 MSEC/DIV) TYPICAL SIGNAL GENERATED BY A NON-MAGNETIC-TYPE FLOW METER.

Figure 9 shows the wave form at a peak to peak voltage of about 30 mV for the magnetic-type meter which is in the range where the Btu meter cannot pick up the reading. This problem can be rectified by inserting a low-pass signal filter and pre-amplifier between the flow meter and Btu meter. Some initial tests indicate that the 3 ft/s (0.914 m/s) can be improved to 1 to

2 ft/s (0.31 to 0.610 m/s). Unfortunately, this type of filter/pre-amplifier is currently not incorporated by manufacturers of either the magnetic paddlewheel flow meter or by manufacturers of the thermal energy meters.

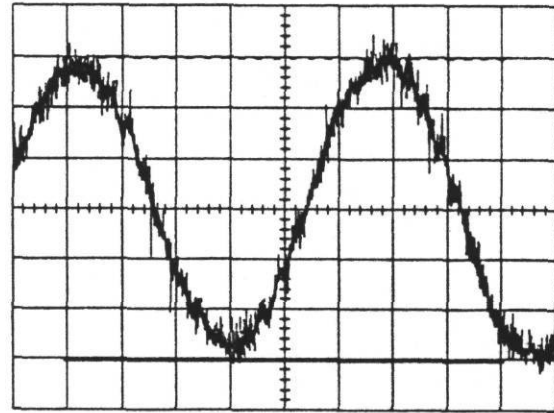


FIGURE 9: (5 MV/DIV, 20 MSEC/DIV) LOW VOLTAGE THRESHOLD FOR THE MAGNETIC-TYPE METER. 30 MV PEAK TO PEAK THRESHOLD BELOW WHICH ONE SPECIFIC THERMAL ENERGY METERS FAILS TO REGISTER PULSES FROM THE FLOW METER.

At higher frequencies (i.e., frequencies corresponding to flow rates greater than ~5 ft/s (~1.52 m/s, or safely out of the low flow regime) magnetic flow meters and non-magnetic flow meters operate identically. With the present set-up, a top end frequency of 57 Hz was obtained with the non-magnetic-type flow meter and 25 Hz for the magnetic-type flow meter. Figures 10a,b show the wave form for each type of flow meter in the higher frequency range. While operating at these frequencies, both types of flow meters exhibited noticeable irregular variations in signal periods. The magnetic-type meter also exhibited a somewhat regular variation in signal amplitude. Both types of variations are thought to be caused by the misalignment of the magnets (or metal matrix density differences in the non-magnetic flow meters). This same variation in the amplitude can signify missing teeth (or blades) in the paddlewheel (which show up as a missing wave), or a worn shaft in the field, which tends to show up as increasing irregularity (i.e., wobble) in the output signal when one compares before/after oscilloscope printouts from the same paddlewheel sensor. Both problems would indicate that the flow sensor needs to be replaced.

Another signature that indicates problems, including a possible worn shaft is the presence of sympathetic vibrations at specific frequencies. This signature is illustrated in Figure 11. The data for this figure were created by slowly increasing the velocity of the air stream across the paddlewheel, pausing at

the different velocities to obtain the average measurements shown, until the onset of vibration¹⁵. This onset can be seen in

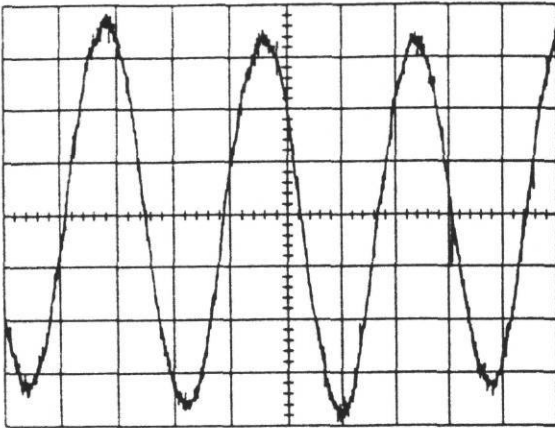


FIGURE 10A: (10 MV/DIV, 20 MSEC/DIV) SIGNAL GENERATED BY 'NORMAL' OPERATING FREQUENCY RANGE OF MAGNETIC-TYPE FLOW METER. THE VARIATION IN AMPLITUDE REPRESENTS MISALIGNMENT IN SENSOR MAGNETS.

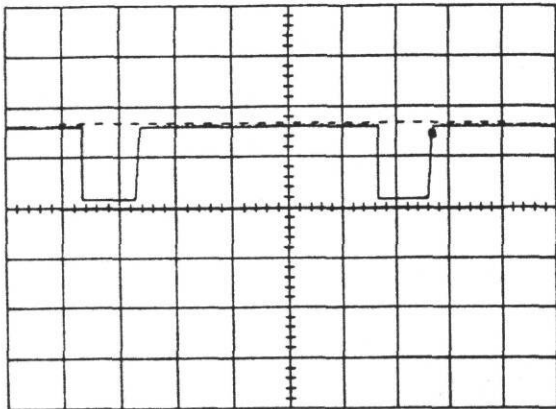


FIGURE 10B: (5 VOLTS/DIV, 5 MSEC/DIV) SIGNAL CHARACTERISTIC OF NORMALLY OPERATING NON-MAGNETIC-TYPE FLOW METER

the data as the discrete downward drop in the rotational speed of the paddlewheel at an air speed of about 18 ft/s (5.5 m/s). The drop occurs because the rotational speed of the paddlewheel slows down at this speed¹⁶ and then resumes picking up speed at some new offset to the original slope of

¹⁵ This sympathetic vibration is probably less pronounced if the flow meter is inserted into a pipe containing water.

¹⁶ This is usually accompanied by an audible squeal or whining noise.

points which causes an erroneous reading for the flow meter. This condition was observed during the inspections

of paddlewheel sensors that had been in service in high velocity flows (10+ ft/s, 3.01 m/s) for a 12 month period. This condition also occurs in flow sensors that are placed near to sources of turbulence. This condition can be indicating severe shaft wear which occurs in both magnetic and non-magnetic-type flow meters.

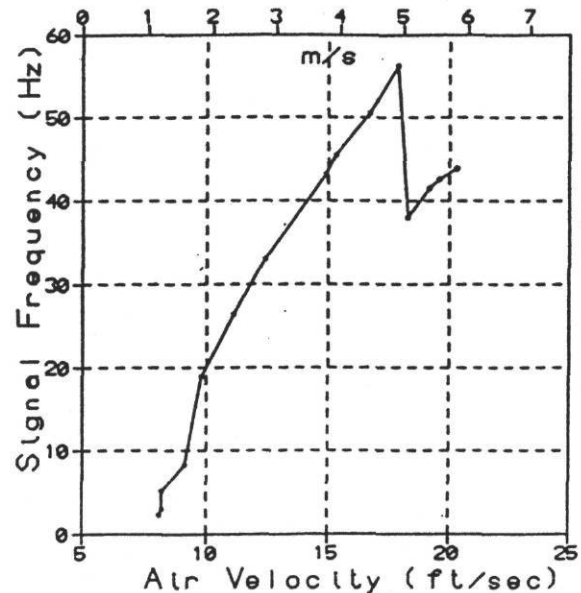


FIGURE 11: SIGNATURE FOR SYMPATHETIC VIBRATION. THIS FIGURE SHOWS THE SIGNATURE FOR A SYMPATHETIC VIBRATION SIMILAR TO THAT EXHIBITED BY EXCESS SHAFT WEAR.

DISCUSSION

The premature drop-out exhibited by the tangential, magnetic-type paddlewheel flow meter at 3 ft/s (0.91 m/s) has been shown to be related to 60 Hz noise in the sensor output signal and a mismatch between the low-end voltage output and the input threshold for the thermal energy meter. The drop-out of the magnetic-type flow meter can be significantly improved with proper shielding and a low-pass filter/pre-amplifier as suggested by Robinson et al. (1992). Another possible solution is to use a frequency to voltage converter between the magnetic flow meter and thermal energy meter to transform the sine wave to a square wave much like the signal generated by the non-magnetic-type meter (Doebelin 1990, Miller 1989).

Perhaps the most important attribute exhibited by the wave forms of both types of flow meters was the variation associated with signal period as well as the variation of amplitude in the magnetic-type flow meter. These variations in the signal period can be attributed to two things: 1) extreme fluid flow variations (i.e., severe turbulence) and 2) a vibration in the paddlewheel due to severe shaft wear. Paddlewheel

meters with worn shafts also tend to be accompanied by a mode of sympathetic vibration which can be detected upon inspection in the field by slowly increasing the speed of the rotor until an audible squeal or whining noise can be heard. Any sensor displaying this characteristic needs to have the shaft replaced.

In previous studies it has been shown that incorrect readings can occur from flow sensors that are subject to transitional flow (Goswami 1991). Experience with the calibration and recalibration of sensors in the LoanSTAR program has shown that incorrect readings can also occur in thermal measurements where the sensor is suffering from improper placement or is too close in proximity to a bend in the pipe (Parker and O'Neal 1995). In some cases this can yield an incorrect measure of the average fluid flow in the pipe. With the careful use of an oscilloscope during the in-situ testing¹⁷, it is possible to determine whether or not a given location may be too turbulent to obtain the proper average measurements before months of data are taken. Severe turbulence should also be avoided because it can lead to premature shaft wear, and the corresponding sensor failure.

The variation of amplitude associated with the magnetic-type flow meter can also be attributed to magnet position in the paddlewheel. These variations seem to follow a more regular pattern than the random variations associated with turbulent flow or shaft wear. Monitoring of the signal amplitude with an oscilloscope in the field can reveal several additional defects in the paddlewheel assembly such as a missing magnets (i.e., a chipped rotor or paddlewheel) or a paddlewheel that has been inserted backwards¹⁸.

In general, in the LoanSTAR program, paddlewheel sensors are pulled and calibrated annually. In the first several years of monitoring roughly eleven out of seventy-five flow meters had to be replaced because of low flow conditions. Two flow meters experienced excessive shaft wear or shaft failures. Clearly, flow meters require special attention during installation including insertion depth, proper alignment, placement in regards to the proper number of pipe diameters downstream from pipe bends (Parker and O'Neal 1995) or obstructions, appropriate flow velocity, and other details such as proper shielding of sensor wires, etc. (Boecker 1992). Since site visits and calibrations can be expensive, diagnostic measures, such as those suggested in this paper, can help to discover which sensors need further attention and thus hold down on unnecessary pulling of sensors during site visits.

Finally, it has been shown that less expensive magnetic-type tangential paddlewheel flow meters can be used with some certainty if flow velocities can be held well above 3 ft/s (0.91 m/s). With the use of a low-pass filter and pre-amplifier and proper shielding magnetic-type paddlewheel meters can be used in flow velocities as low as 2 ft/s (0.61 m/s). In installations where velocities are below 2 ft/s (0.61 m/s) and above 1 ft/s (0.31 m/s) non-magnetic-type paddlewheel meters

seem to have the edge. The use of tangential paddlewheel sensors of any kind in velocities below 1 ft/s (0.31 m/s) is not recommended. In such cases a special purpose metering leg may need to be installed that diverts the fluid flow through a smaller diameter pipe so that higher velocities can be obtained. Both the magnetic and non-magnetic tangential paddlewheel flow meters performed well within the manufacturer's specification as shown in Table 2.

TABLE 2: SUMMARY OF EXPERIMENTAL RESULTS. THIS TABLE GIVES A SUMMARY OF THE EXPERIMENTAL RESULTS SHOWN IN FIGURES 3A AND 3B. COEFFICIENT OF VARIATION CV(RMSE) AND MBE WERE CALCULATED USING THE EQUATIONS IN THE APPENDIX. DATA SHOWN CORRESPOND TO FIGURES 3A AND 3B¹⁹.

	CV(RMSE) %	MBE %
Magnetic meter	1.99	-0.11
Non-magnetic meter	2.31	+1.80
Both meters	2.13	+0.81

It may be useful to measure in-situ quiescent-state noise from a sensor when making the determination as to whether or not to specify a less expensive magnetic-type sensor. It may also be useful to periodically record a "snapshots" of the oscilloscope screen during installation and keep it for comparison purposes since this can serve as a useful record of the rotational characteristics of the paddlewheel sensor. This can be accomplished with any digital storage oscilloscope.

Hence, it is recommended that tangential paddlewheel sensors be checked every 12 months for any of a variety of problems, including: shaft wear, missing rotor blades, or unusual turbulence. If fluid velocities at a site are consistently above 8 to 10 ft/s (2.4 to 3.05 m/s) a more robust type of sensor might be recommended that does not contain rotating mechanisms that could wear out, for example an averaging pitot tube, shedding vortex meter or target-type meters.

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¹⁷ Or other sensitive, time-varying frequency monitoring device.

¹⁸ A sensor that is placed backwards has a wave form of lower amplitude and frequency. The drop-out velocity will also be greater than normal.

¹⁹ Data for the 6-inch pipe were excluded due to a known problem involving a non-uniform flow field that is not representative of normal field conditions.

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APPENDIX

The statistical indices used to evaluate the flow data are defined as (Kreider and Haberl 1994, SAS 1990):

The coefficient of variation of the root mean square error CV(RMSE) is defined in percent (%) as:

$$CV = \frac{\sqrt{\frac{\sum_{i=1}^n (y_{pred,i} - y_{data,i})^2}{n - p}}}{\bar{y}_{data}} \times 100$$

and the mean bias error (MBE) is given by

$$MBE = \frac{\sum_{i=1}^n (y_{pred,i} - y_{data,i})}{n - p} \times 100$$

where

$y_{data,i}$ = is the data value of the dependent variable

corresponding to a particular set of the independent variables,

$y_{pred,i}$ = is the predicted dependent variable value for the same set of independent variables above,

\bar{y}_{data} = is the mean value of the dependent variable of the data set,

n = is the number of data points in the data set,

p = is the total number of regression parameters in the model (which was arbitrarily assigned as 1).

TABLE 1: SUMMARY OF FLOW METER CHARACTERISTICS. THIS TABLE PRESENTS A SUMMARY OF FLOW METER CHARACTERISTICS ASSEMBLED FROM A SURVEY OF MANUFACTURERS AND FROM EXPERIENCES WITH THE LOANSTAR PROGRAM, AND OTHER USEFUL SOURCES (HABERL ET AL. 1992B).

FLOW METER	D I R T Y	C L E A N	RANGABILITY	L O W F L O W	PURCHASE COSTS (\$)	INSTALL COST (\$)	ACCURACY UNCALIBRATED (INCLUDE TRANSMIT.) (SEE NOTE 1)	APPLICATIONS
ORIFICE PLATE	A	G	RANGE OF ALL DIFFERENTIAL METERS IS LIMITED BY THE RANGE OF THE PRESSURE TRANSDUCER IN USE	G	\$800	\$1500	± 1-2 % FULL RANGE SCALE (FRS)	GOOD FOR LOW FLOWS IN CLEAN WATER
VENTURI TUBE	G	G		G	\$1500	\$1500	± 1-2% FRS	GOOD FOR CONTROLS & MONITORING IF PRESENT
NOZZLE	G	G		G	\$2000	\$2000	± 1-2% FRS	GOOD FOR STEAM AND HIGH PRESSURE GASSES
PITOT TUBE	P	G		G	\$500	\$500	± 5% FRS	GOOD FOR SPOT CHECKS IN CLEAN FLUID
ANNUBAR	P	G		G	\$1500	\$500	± 1% OF RATE	VERY GOOD FOR LOW FLOW IN CLEAN FLUID
TURBINE	P	G	1-30 FPS	P	\$1500	\$1500	± 1% OF RATE	VERY GOOD METER IN CLEAN FLOW
VORTEX	G	G	1-30 FPS	G	\$3500	\$1500	± 5-15% OF RATE	GOOD MULTI PURPOSE METER
TANGENTIAL PADDLEWHEEL	A	G	1-30 FPS	P	\$300-500	\$500	± 2.5% OF RATE	GOOD FOR MONITORING
INSERTION TURBINE	P	G	1-30 FPS	P	\$1500	\$500	± 1% OF RATE	GOOD FOR MONITORING
TARGET	A	G	1-30 FPS	P	\$1500	\$500	± 1.5-5% FRS	GOOD FOR MONITORING
ULTRASONIC TIME OF FLIGHT	G	G	5-30 FPS	A A	\$2000-\$3500	\$500	± 5 %FRS ± 5% FRS	GOOD FOR SPOT CHECKS
DOPPLER	G	G	5-30 FPS					
MAGNETIC	G	G	5-30 FPS					
MASS FLOW	A	G	5-30 FPS	G	\$3000	\$1500	± 1% FRS	GOOD METER IF BUDGET IS NOT A FACTOR
				G	\$3500	\$1500	± 2-1% FRS	GOOD IN LOW CLEAN FLOW AND SMALLER PIPES

G - GOOD A - AVERAGE P - POOR

NOTE: 1. VALUES FROM MILLER 1989.

2. OTHER VALUES IN THIS TABLE ARE APPROXIMATE AND ARE GIVEN AS REFERENCE VALUES. PRICES AND CHARACTERISTICS WILL CHANGE AS CONDITIONS DICTATE.